

Validation of High-Resolution CFD Method for Slosh Damping Extraction of Baffled Cryogenic Propellant Tanks

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Propellant slosh is a potential source of disturbance critical to the stability of space vehicles. The slosh dynamics are typically represented by a mechanical model of a spring-mass-damper. This mechanical model is then included in the equation of motion of the entire vehicle for Guidance, Navigation and Control analysis. A Volume-Of-Fluid (VOF) based Computational Fluid Dynamics (CFD) program developed at MSFC was applied to extract slosh damping in the baffled tank from the first principle. First the experimental data using water with sub-scale smooth wall tank were used as the baseline validation. It is demonstrated that CFD can indeed accurately predict low damping values from the smooth wall at different fill levels. The damping due to a ring baffles at different depths from the free surface was then simulated, and fairly good agreement with experimental measurement was observed. Comparison with an empirical correlation of Miles equation is also made.

Propellant slosh is a potential source of disturbance critical to the stability of space vehicles. The slosh dynamics are typically represented by a mechanical model of a spring mass damper. This mechanical model is then included in the equation of motion of the entire vehicle for Guidance, Navigation and Control analysis. The typical parameters required by the mechanical model include natural frequency of the slosh, slosh mass, slosh mass center location, and the critical damping ratio. During the 1960's US space program, these parameters were either computed from an analytical solution for a simple geometry or by experimental testing of sub-scale configurations. Since the liquid oscillatory frequency may nearly coincide with either the fundamental elastic body bending frequency or the dynamic control frequency of the vehicle at some time during the powered phase of the flight, the slosh forces could interact with the structure or control system. This could cause a failure of structural components within the vehicle or excessive deviation from its planned flight path [1]. It is, therefore, necessary to consider means of providing adequate damping of the liquid motions and slosh forces and to develop methods for accounting for such damping in the vehicle performance analyses.

In order to meet the damping requirement by flight control, baffles of various configurations have been devised to increase the natural viscous damping and decrease the magnitude of the slosh forces and torques [1].

Slosh Damping Estimation and Baffle Design Using Empirical Correlations

Determination of slosh damping in a given tank configuration is a very challenging task. First, an analytical solution does not currently exist for the slosh damping due to high nonlinearity of the problem. While slosh frequency can be computed using linear potential theory, the damping physics involves the vorticity dissipation which requires the full solution of the nonlinear Navier-Stokes equations. Previous investigations and knowledge of damping characteristics were mainly carried out by extensive experimental studies.

Slosh Damping Correlation for Smooth Wall Cylindrical Tank

Four extensive experimental studies have been carried out on viscous damping in circular cylinders [2-5], and the damping values have been correlated to a functional form of:

$$\gamma = C\sqrt{\text{Re}} \quad (1)$$

where Re is a dimensionless parameter analogous to an inverse Reynolds number [7]:

$$\text{Re} = \frac{\nu}{\sqrt{gR^3}} \quad (2)$$

and C is a constant, γ is the damping ratio or the critical damping ratio of the amplitude of the free surface oscillation. R is the tank radius, g is the gravity acceleration and ν is the kinetic viscosity of the liquid.

Mikishev and Dorozhkin [5] proposed the following correlation from their tests [6]:

$$\gamma = 0.79\sqrt{\text{Re}} \left[1 + \frac{0.318}{\sinh(1.84h/R)} \left(1 + \frac{1-h/R}{\cosh(1.84h/R)} \right) \right] \quad (3)$$

where h is the liquid depth. For large depth of $h/R > 1.0$, the above equation may be approximated by:

$$\gamma = 0.79\sqrt{\text{Re}} \quad (4)$$

A similarly extensive but independent study by Stephens *et al.* [4] found a slightly different correlation:

$$\gamma = 0.83\sqrt{\text{Re}} \tanh(1.84 \frac{h}{R}) \left[1 + 2 \frac{1-h/R}{\sinh(3.68h/R)} \right] \quad (5)$$

When the liquid depth is large, equation (5) reduces:

$$\gamma = 0.83\sqrt{\text{Re}} \quad (6)$$

The above correlations have become industry standard methodology to compute slosh damping value over a smooth wall.

Slosh Damping Correlation for Baffled Cylindrical Tank

Fuel-slosh damping by ring baffles in cylindrical tanks has been investigated both theoretically and experimentally [8-12]. A survey of damping measurements obtained in various experiments shows many apparent discrepancies. The most widely used damping equation at present is the one obtained by Miles [11] which is based on experiments of Keulegan and Carpenter [12]. The equation is written as:

$$\gamma = 2.83e^{-4.6(h_s/R)} C_1^{3/2} \left(\frac{\delta}{R}\right)^{1/2}; \quad C_1 = \frac{w}{R} \left(2 - \frac{w}{R}\right) \quad (7)$$

Here, h_s , w , and C_1 respectively denote the baffle depth, width and blockage ratio, while δ , R denote the slosh wave amplitude and local tank radius. These symbols are shown in Figure 1. On the right hand side of Figure 1 is the comparison of the above equation to the test data.

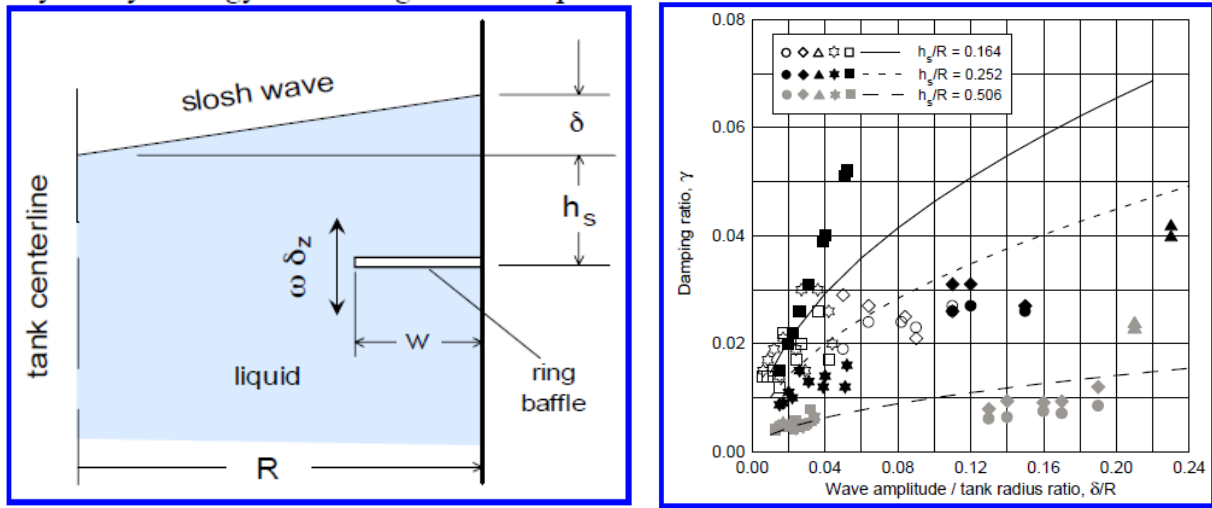


Figure 1. Schematic of ring baffle and damping in a cylindrical tank

Modified Miles Equation for the Upper Dome of a Tank

The above Miles equation is derived from a straight cylinder. For the upper dome, depending on the liquid fill level, an effective baffle area coefficient C_{EBA} has been proposed (see Figure 2) [13]:

$$C_{EBA} = \frac{A_{inner}}{A_{baffle}} = \frac{r^2 - r_i^2}{r_o^2 - r_i^2}, \quad (8)$$

r : local fill level radius; r_i and r_o : baffle inner and outer radius

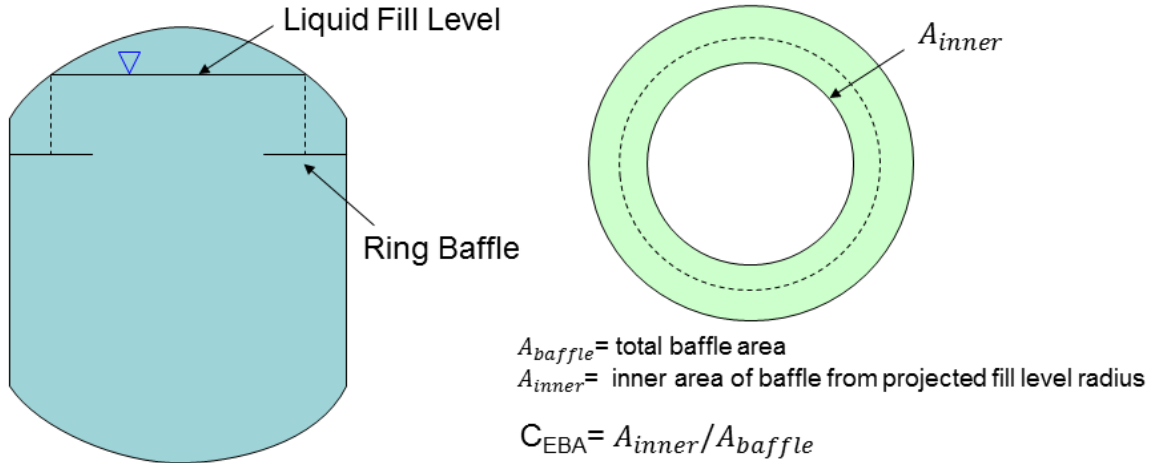


Figure 2. Definition of effect area coefficient based on the fill level for modified Miles equation.

Now the modified Miles equation can be written:

$$\gamma = 2.83e^{-4.6(h_s/R)} C_1^{3/2} \left(\frac{\delta}{R}\right)^{1/2} \frac{(r_o^2 - r_i^2)}{(r_o^2 - r_i^2)}; \quad C_1 = \frac{w}{R} \left(2 - \frac{w}{R}\right) \quad (9)$$

1.1 Slosh Damping Calculation Using CFD Technology

ER42 at MSFC has been active in applying CFD technology to extract slosh damping parameters. An early work [14] has demonstrated the soundness of a CFD approach in modeling the detailed fluid dynamics of tank slosh and has shown excellent accuracy in extracting the mechanical properties for different tank configurations as a function of the fill level. The verification and validation studies included a straight cylinder against an analytical solution, and sub-scale Centaur LOX and LH2 tanks with and without baffles against experimental results for the slosh frequency, slosh mass, and mass center. The study shows that CFD technology can provide accurate mechanical parameters for any tank configuration and is especially valuable to the future design of propellant tanks, as there is no previous experimental data available for the same size and configuration as the current flight designs.

For a practical partially-filled smooth wall propellant tank with a diameter of 1 meter, the damping ratio is as low as 0.0005 (or 0.05%). To accurately predict this very low damping value is a challenge for any CFD tool, as one must resolve a thin boundary layer near the wall and must minimize numerical damping. To improve the understanding of the physics behind slosh damping, the authors have taken a fundamentally sound approach [15] first with validations against experiments for the smooth wall cylindrical tank. High-order numerical schemes were applied using a technique developed to estimate and reduce/remove the numerical damping from the solution. With the validated CFD model, a study was made with the damping in the presence of a flat ring baffle which is a commonly used as means of slosh suppression. It is demonstrated that with proper grid resolution, CFD can indeed accurately predict low damping values from smooth walls for different tank sizes. The damping due to ring baffles at different depths from the free surface and for different sizes of the tank was then simulated, and fairly good agreement with experimental correlation was observed.

In the recent years, NASA/MSFC has been developing a Volume-of-Fluid (VoF) approach within the unstructured mesh, pressure-based algorithm CFD program, Loci-STREAM-VOF [16].

VALIDATION FOR SMOOTH WALL CYLINDER AS A FUNCTION OF FILL LEVEL

An analytical expression is available to compute the sloshing frequency in a smooth wall cylindrical tank as a function of acceleration and fill level[1]. Empirical correlations are available to compute the critical slosh damping in a smooth wall cylindrical tank as a function of acceleration and fill level [1]. In addition, experiments were conducted at NASA/MSFC in 2011 which provided similar data[20]. The results of the analytical expressions, empirical correlations, experimental data and CFD simulation results of Loci-STREAM-VoF are shown in Figure 3 for the reduced slosh frequency and Figure 4 for the critical slosh damping. In each figure, the simulation results of Loci-STREAM-VoF are consistent with the experimental data. In Figure 4, the experimental data indicates that the empirical correlation under-predicts the critical damping and the CFD predictions are in agreement with the experimental data on this issue.

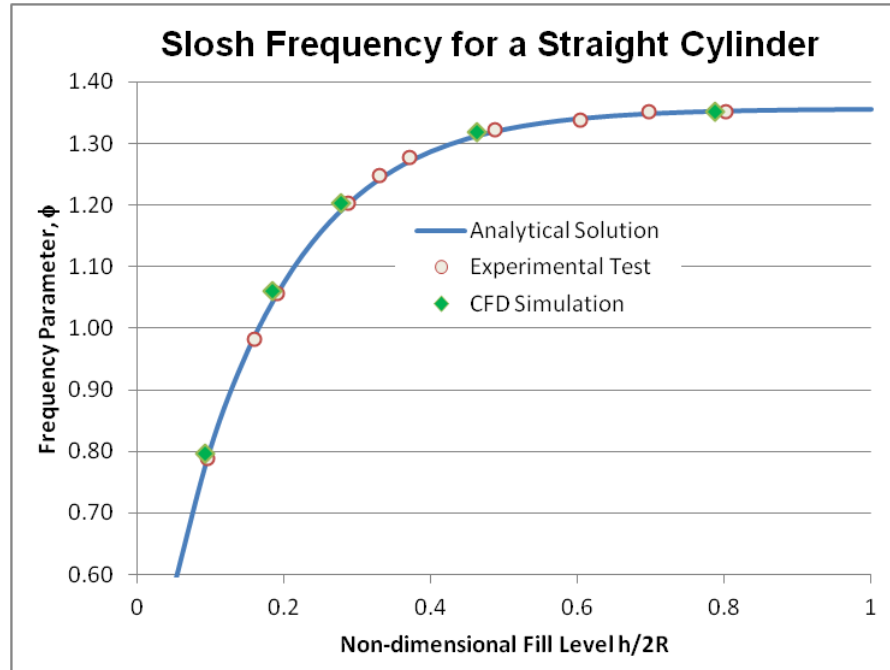


Figure 3. Frequency as a function of liquid fill level in a straight cylinder.

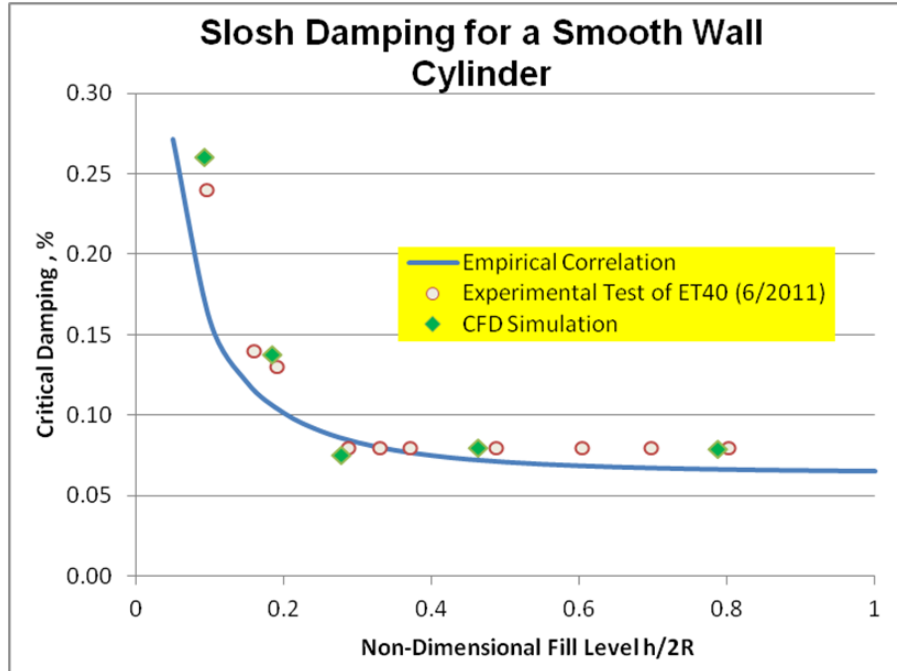


Figure 4. Critical damping as a function of liquid fill level in a straight cylinder

VALIDATION FOR BAFFLED TANK AS A FUNCTION OF FILL LEVEL

An empirical correlation, the Miles Equation[11], is available to compute the critical damping in a propellant tank in the vicinity of a baffle. In addition, experiments using water were conducted at NASA/MSFC in 2011 to investigate the damping characteristics of propellant tank baffles[20]. The experimental setup diagram and an image of the test article are contained in Figure 5.

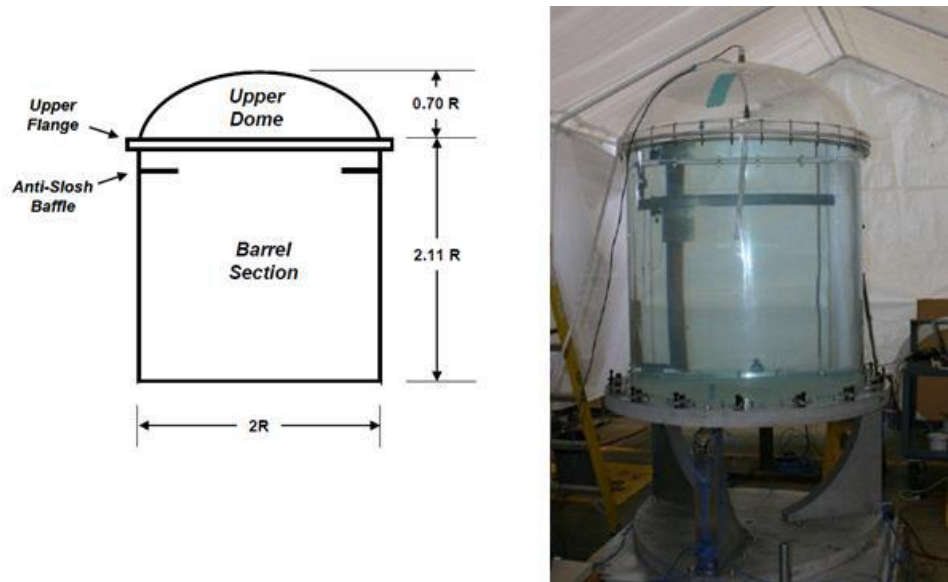


Figure 5 Slosh critical damping values as a function of tank fill level from empirical correlation, recent experiments, and Loci-STREAM-VoF simulation results.

A structured mesh was constructed with 5.7 million cells based on previous experience with this scale of the tank. The nature of the mesh is depicted in Figure 6. The fluid level initial condition chosen

was a linear profile rotated an angle with respect to the gravity vector which was oriented downwards. . The velocity and initial pressure conditions were quiescent and constant pressure respectively. The baffle is located at a tank height of 43.91 inches. The fill levels investigated were all above the baffle station and were: 44.84, 45.56, 46.64, 48.07, 49.16, 51.19 and 53.19 inches.

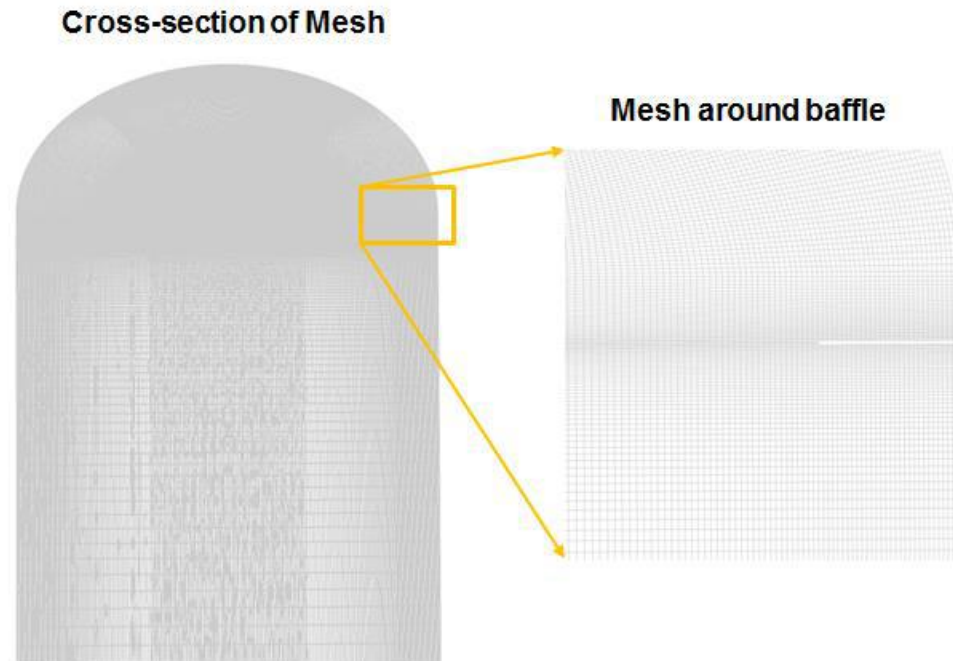


Figure 6 Details of structured mesh constructed to simulate slosh in the baffled tank configuration. Mesh size is 5.7 million cells.

A snapshot of the CFD solution for the fill level of 44.84 inches is shown in Figure 7. The liquid surface's interaction with the baffle has results in significant deformation of the fluid-gas interface, resulting in surface roll-up and trapped gas bubbles above the baffle. Velocity vectors indicate significant secondary flows above the baffle.

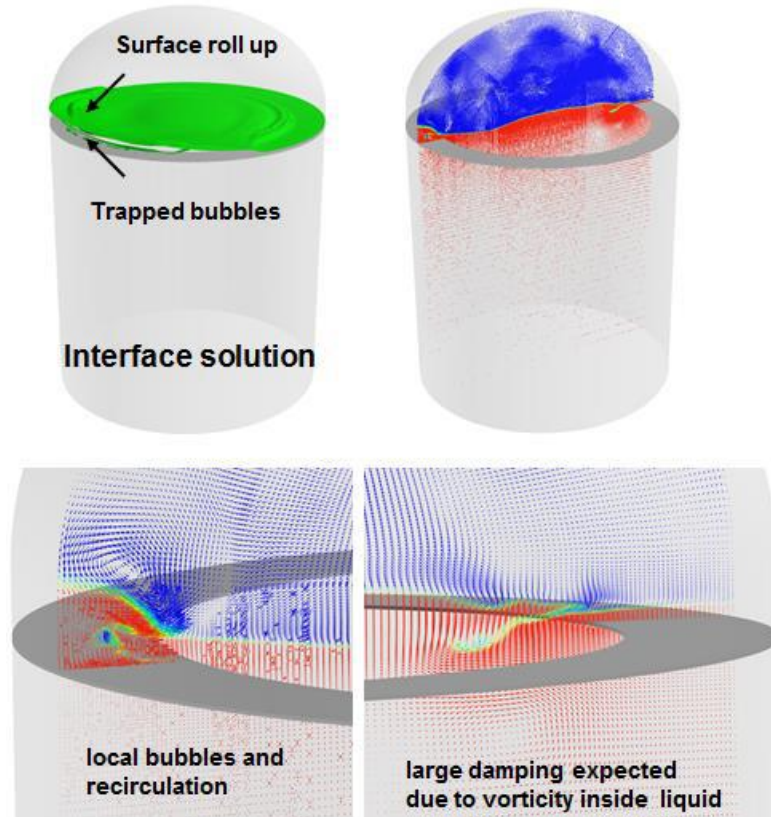


Figure 7 Details of CFD flowfield for the fill level of 44.84 inches. The fluid-gas interface is shown in upper left. The velocity vectors are colored by fluid density with red indicating liquid phase.

A snapshot of the CFD solution for the fill level of 48.07 inches is shown in Figure 8. The liquid surface's interaction with the baffle has results in significant deformation of the fluid-gas interface, resulting in surface shapes revealing higher order slosh modes than present in the initial conditions. Velocity vectors indicate significant secondary flows above and below the baffle.

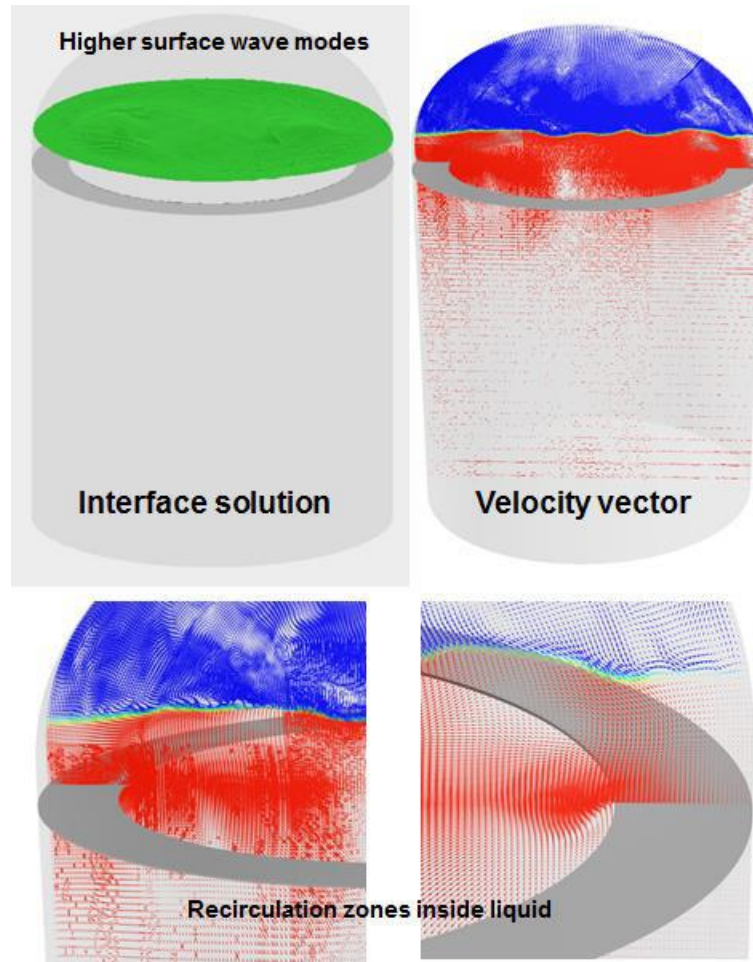


Figure 8 Details of CFD flowfield for the fill level of 48.07 inches. The fluid-gas interface is shown in upper left. The velocity vectors are colored by fluid density with red indicating liquid phase.

A snapshot of the CFD solution for the fill level of 53.19 inches is shown in Figure 9. The fill level is above the cylindrical, spherical transition. The liquid surface's interaction with the baffle has results in some deformation of the fluid-gas interface. Velocity vectors indicate significant secondary flows above and below the baffle.

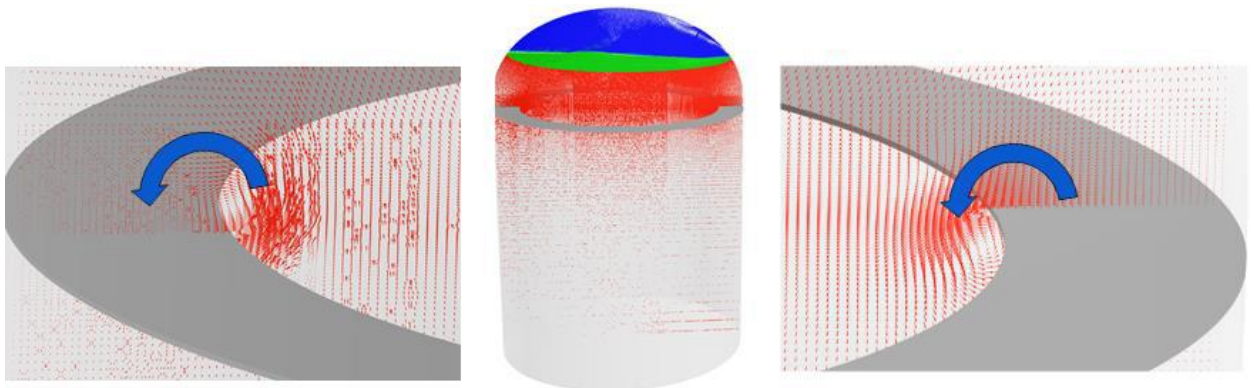


Figure 9 Details of CFD flowfield for the fill level of 53.19 inches. The fluid-gas interface is shown in the top middle. The velocity vectors are colored by fluid density with red indicating liquid phase.

A significant effort was required to compute slosh damping rates from the CFD simulation results. The method used was that described in a previous section. The complicating factor is that for fill levels close to the baffle location, damping is a significant function of slosh amplitude. The solution to the difficulty was to examine the MSFC experimental data[20] and determine the slosh amplitude at which the experimental value of damping was determined. The damping from the CFD simulation results was computed at the same slosh amplitude as the experimental post processing. In this manner, the comparison between experimental results and CFD simulation results was constructed. Figure 10 contains the comparison of the critical damping determined from the Miles Equation, the MSFC experimental data, and Loci-STREAM-VoF as a function of the normalized fill level. For critical damping values above 2 percent, all three methods produce equivalent results. For the highest fill level, the experimental and CFD damping is significantly greater than the Miles Equation.

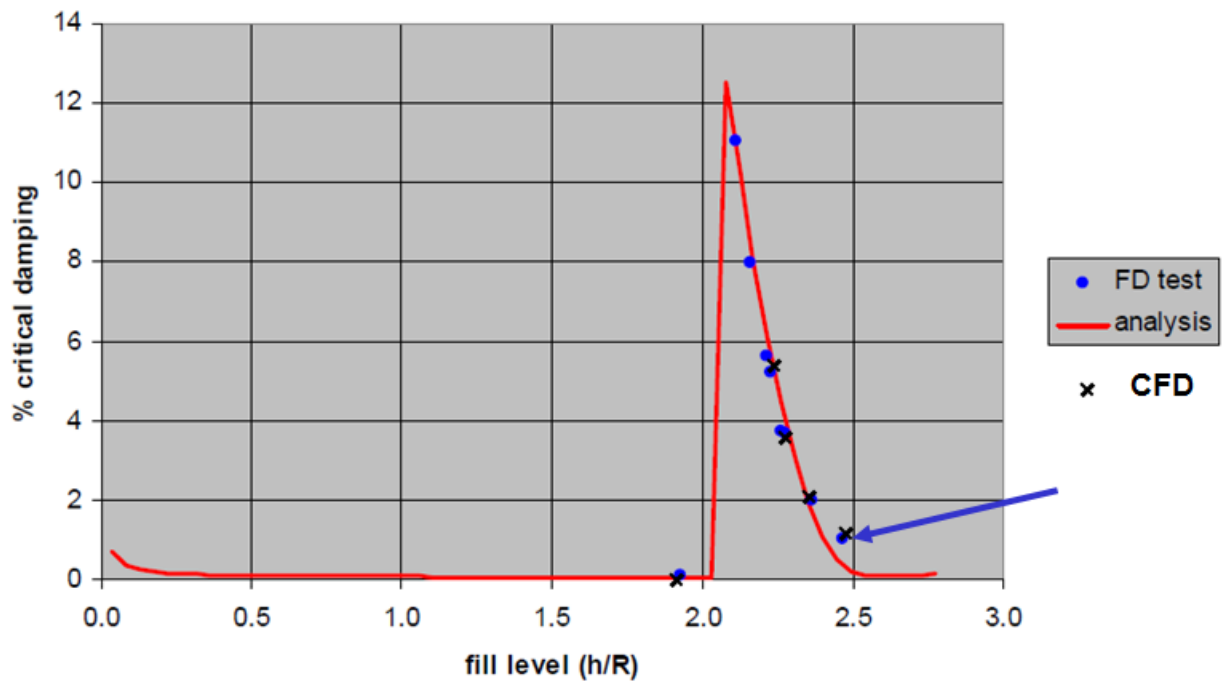


Figure 10 Percent critical damping as a function of normalized fill level from the Miles Equation (analysis), experimental data and Loci-STREAM-VoF (CFD).

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